

Turbulent Diffusion Behind Vehicles
Experimentally Determined Turbulence
Mixing Parameters

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TURBULENT DIFFUSION BEHIND VEHICLES: EXPERIMENTALLY DETERMINED TURBULENCE MIXING PARAMETERS

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Abstract—The wake of a moving vehicle was simulated using a specially constructed wind tunnel with a moving floor. A 'block-shaped' model vehicle was fixed in position over the test-section floor while the floor moved at the freestream air speed to produce a uniform, shear-free, approach flow. This simulates an automobile traveling along a straight highway under calm atmospheric conditions.

Vertical and lateral profiles of tracer gas concentration were obtained in the wake. Profiles were taken at distances of 30, 45 and 60 model heights downwind. The equations describing the wake theory were solved numerically to determine the 'best' turbulence scale lengths by using wind tunnel data taken at 30 model heights downwind as the inflow boundary condition and comparing the numerical computation made at 60 heights downwind to the wind tunnel data taken at this location. It was found that the 'best' scale lengths were the vehicle width along and across the wake, and height above the surface in the vertical directions, respectively.

The ROADWAY model, in which the computer code incorporates the wake theory to predict air pollution concentrations along highways, was modified with these new results and found to better predict the General Motors data than the initial version of the model.

Key word index: Cars, exhaust emissions, line source, ozone chemistry, vehicle wakes, wake model, wind tunnel.

NOMENCLATURE

A	Constant giving the strength of the wake
a_1, a_2, a_3	constants in the turbulent kinetic energy equation
B_m	analytic operators representing advection and diffusion
C_d	drag coefficient
E_A, E_D, E_C	vehicle emissions in $\text{g km}^{-1} \text{veh}^{-1}$
f	function giving vertical and lateral variation of velocity deficit
F_c	function describing cross-sectional variation of turbulent kinetic energy term
H	height of the vehicle
K_i	nondimensional eddy diffusion coefficient in the i -th direction
$\tilde{K}_i$	dimensional eddy diffusion coefficient in the i -th direction
K_i^s	eddy diffusion coefficient in the i -th direction determined from surface layer similarity theory
K_i^w	eddy diffusion coefficient in the i -th direction determined from vehicle wake theory
$l(s)$	vertical scale length of the velocity deficit
L_i	operators representing finite difference approximations of the advection and diffusion operators

Q	wind speed relative to the vehicle
(s, n, z)	coordinate system oriented along, across the wake and z is the vertical axis
$(\bar{x}, \bar{y}, \bar{z})$	similarity coordinates used in the velocity deficit solution
u	wind speed in the i -th direction
u_i^2	i -th component of turbulent kinetic energy
u_D	velocity deficit behind the vehicle
U_∞	x component of the upwind ambient wind speed
v	wind speed in the i -th direction
V_h	vehicle speed
V_∞	y component of the upwind ambient wind speed
$\bar{v}^2$	j -th component of the turbulent kinetic energy
w	vertical component of the wind speed
W_0	width of the vehicle
w^2	z -component of turbulent kinetic energy
x, y, z	coordinate system fixed in standard east-west, north-south orientation, z is vertical coordinate.

1. INTRODUCTION

It is now known that turbulence near busy highways is dominated by vehicle-generated eddies. Various empirical approaches have been taken to parameterize the

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effects of vehicle-induced turbulence, but until recently there did not exist a theoretical description of vehicle wakes. Eskridge and Hunt (1979) derived from the equations of motion a solution which describes the mean velocity deficit in the wake, and they estimated the wake turbulence by assuming that the turbulence scale lengths were the same as the velocity scale lengths. Wind tunnel experiments by Eskridge and Thompson (1982) verified the theoretical description of the velocity deficit, but it was found that the turbulence scales are different from the velocity scales.

The theoretical description of the velocity deficit was modified by Eskridge and Thompson (1982), but the observed strong shear near the surface was not explained completely by the theory. The existence of a large shear near the surface is incompatible with the assumption of a constant eddy viscosity as made by Eskridge and Hunt (1979). Eskridge and Rao (1983) fitted a curve to wind tunnel data to better simulate the vertical variation of velocity near the surface and retained the velocity length scales which were shown to be valid. The results in the above papers were used in the development of the ROADWAY model which is used to predict velocity and turbulence fields and pollutant concentrations near highways. A summary of the ROADWAY model is given in the Appendix.

Pollutant diffusion in the initial version of the ROADWAY model was assumed to be describable by using eddy diffusion coefficients which were given by

$$K_i^x = (\overline{u_i^2}) \cdot H, \quad (1)$$

where H is the vehicle height and $(\overline{u_i^2})$ is the rms value of the velocity fluctuations in the i th direction.

In order to test this hypothesis [i.e. Equation (1)] and versions involving other scale lengths, a series of wind tunnel experiments were conducted using a tracer gas. The techniques used are given in Section 2.

To determine eddy diffusion coefficients which describe the diffusion in the wake region, a numerical model based upon the vehicle wake theory was used to simulate the wind tunnel tracer studies. The results are given in Section 3, where the results of the current version of ROADWAY are compared to the initial version of the model using the data from the General Motors experiment (Cadle *et al.*, 1976).

2. TRACER EXPERIMENTS

2.1. The wind tunnel

A wind tunnel was specially constructed for the vehicle studies. A commercially available conveyor belt assembly was used for the test-section floor and the supporting framework for the entrance, test, and exit sections of the wind tunnel. The test section was 4.75 m long, with a cross section 0.82 m wide and 0.71 m high.

The entrance section had the same cross section dimensions as the test section. A bellmouth around the perimeter of the entrance directed room air into a

section of Vertical (Vertical Co., paper triangular-cell honeycomb; cell length = 0.15 m and hydraulic diameter 0.01 m). Two fiberglass screens (16 by 18 mesh) were placed downwind of the honeycomb to further lower the free-stream turbulence.

The moving floor of the test-section was the rubber conveyor belt. A notched, overlapped joint and large end-rollers produced a smoothly running belt. Rails along the tops of the tunnel walls were installed to support an instrument-traversing mechanism. The longitudinal position of a probe was set manually, and the vertical and lateral positions were remotely set and read from the operator's desk.

The exit section contained a section of Vertical and a lateral contraction to a 0.71 m wide by 0.71 m high cross section. A cast aluminum fan with three blades (diameter of 0.61 m) was powered by a two-speed (1140/1725 rpm), 250 W electric motor. The fan was mounted in a metal shroud for efficient operation. The operating speed of the tunnel during all experiments was 1.9 m s^{-1} . The background turbulence intensity was less than 1%. Homogeneity of the mean flow was checked with the tunnel operating at test conditions by measuring vertical profiles of velocity at various positions in the test section.

2.2. Model vehicles and instrumentation

Simple block-shaped models were constructed of wood; they had the proportions of height, width, and length of a typical automobile. Each model was mounted on a baseplate with wheels and rubber tyres. Approximate scale ratios of 1/32 and 1/8 were used.

The 1/32 scale block-shaped vehicle was patterned on the dimensions of an intermediate-sized American automobile: actual height = 0.043 m, width = 0.055 m, length = 0.145 m, ground clearance = 0.009 m, and wheel diameter = 0.024 m.

Concentration measurements were obtained by introducing a passive hydrocarbon tracer gas into the wake of the vehicle and measuring downstream concentrations with a hydrocarbon analyzer. Ethylene gas was used because its density is very near that of air, simulating a neutrally buoyant effluent. The tracer was injected into the vehicle wake through a porous 'air stone' of the type commercially available for aquarium aeration. This assured that the tracer was injected with minimal momentum in any given direction, limiting any effects due to jetting of the effluent. The tracer flow rate was held constant during all tests and was continuously monitored using a Meriam laminar flow element in conjunction with a water manometer. A Beckman 400 hydrocarbon analyzer (flame ionization detector) was used to measure the tracer concentration downstream of the model. The analyzer was calibrated using hydrocarbon-free air to set a zero scale, and 6760 ppmv ethylene standard gas to set a full scale. The analyzer was shown, in a separate series of tests, to respond linearly to ethylene concentration over four decades of dilution. Samples were continuously

withdrawn through a 0.16-cm diameter sample probe at a rate of 200 cm min^{-1} . The instrument output, an analog voltage, was sampled, digitized, and recorded by a minicomputer system using a twelve-bit analog-to-digital converter. An averaging time of 30 s was found to yield reasonably stable average values. Background hydrocarbon concentration was sampled both before and after each series of measurements and was subtracted from the measured concentrations. The turbulence measurement instrumentation and techniques were described by Eskridge and Thompson (1982).

2.3. Wind tunnel tracer experiments

Eskridge and Thompson (1982) in their wind tunnel experiments found qualitative differences in the velocity structure and turbulence fields of the wake behind a scale model car with aerodynamic lift and that of a block-shaped car which had no lift. To determine how the differences in the velocity and turbulence fields affect the concentration field (i.e. diffusion of pollutants), lateral concentration profiles were taken at $x = 30H$ downwind of the block vehicle and a 1/32 scale Ford Mustang. The concentration profiles were essentially identical from the surface to one vehicle height as shown for $z = 0.75H$ in Fig. 1. Above z

$= 1H$, the centerline concentrations show the effect of the mean vortices created by the lift of the streamlined vehicle. The two vortices bring ambient air into the wake, reducing the concentrations near the centerline of the wake as shown for $z = 1.5H$, in Fig. 2.

Based upon the above findings, only the block vehicle was used in all further experiments. Reasons for this were the following: first, in the region of highest concentration (the surface to $z = H$) the concentration patterns were independent of vehicle shape; second, above $z = H$ the concentrations fell off rapidly and the values behind the block vehicle were higher and hence represent a conservative estimate; and finally as there are hundreds of different vehicles on U.S. highways, the scale model Mustang is not representative of all these different vehicles, nor is any scale model.

Lateral profiles of tracer gas concentrations were taken at heights of $0.25H$, $0.50H$, ..., $3.00H$ at distances of $x = 30H$ and $x = 60H$ downstream of the vehicle (Figs 3 and 4). The spacing in the lateral direction was $0.18W_0$ (W_0 is the vehicle width). These data were fitted by a least-squares orthogonal polynomial in order to later specify the concentration values on a grid. The gridded values of concentration for the cross sections at $x = 30H$ and $x = 60H$ are shown in Figs 5 and 6. The grid values shown in Figs 5

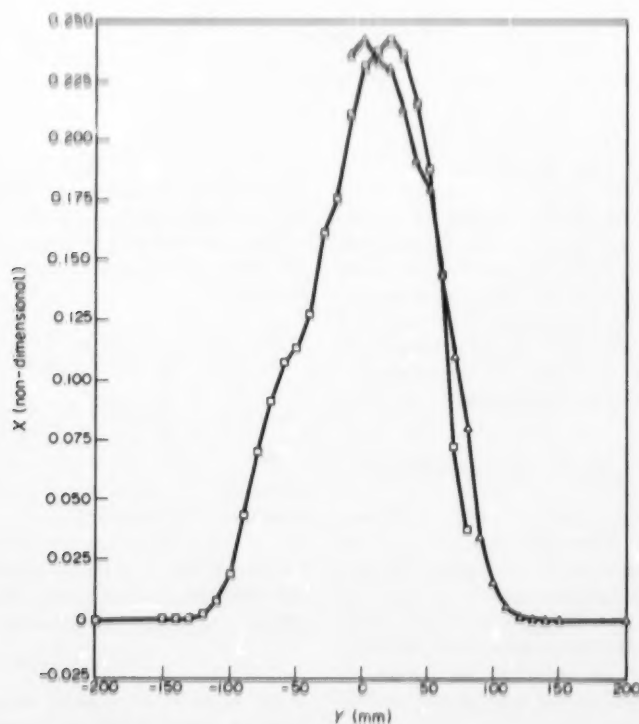


Fig. 1. Plot of lateral profiles of nondimensional concentration at 30 heights downwind of the vehicle model at a height of $0.75H$. The symbols Δ , $\square$ represent the block and Mustang vehicles, respectively. The vehicle is 55 mm wide with its center approximately located at $y = 0$.

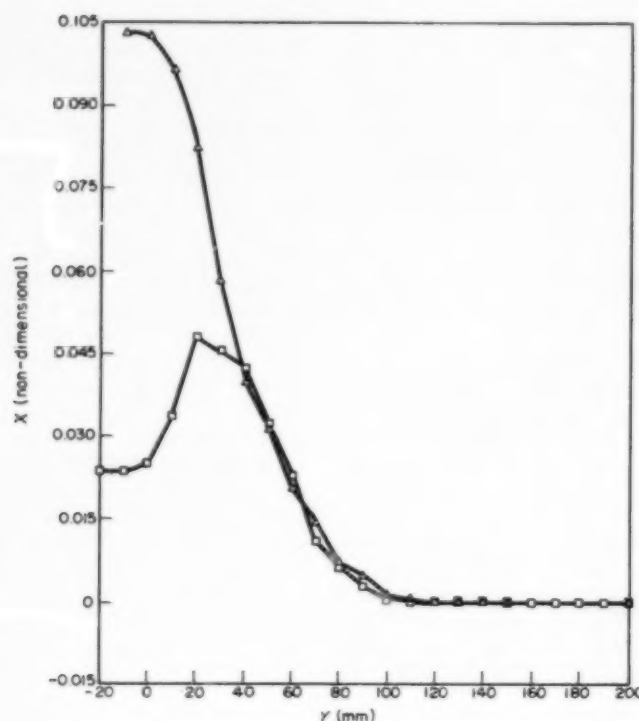


Fig. 2. Plot of lateral profiles of nondimensional concentration at 30 heights downwind of the vehicle model at $z = 1.5H$. The symbols Δ , $\square$ represent the block and Mustang vehicles, respectively.

and 6 were calculated using the previously mentioned orthogonal polynomials. Finally, it should be noted that the concentration patterns downwind of the vehicle will be influenced by a crosswind. Unpublished experimental results indicate that whenever the vehicle speed is a factor of ten greater than the crosswind speed, changes in the concentration distribution will be minor. Major differences in the concentration pattern will probably exist when the vehicle speed is less than five times the crosswind speed.

3. SIMULATION OF THE TRACER EXPERIMENTS

There is no direct method of extracting a turbulence length scale from the concentration data that would yield a 'best' formulation for the eddy diffusion coefficients. An alternate approach is to solve the applicable equations and boundary conditions numerically. Numerical simulations were performed with the various candidates for the turbulence length scale, and model predictions were compared to the wind tunnel measurements.

The numerical model consists of a diffusion equation and the vehicle wake theory. The data taken at $s = 30H$ in the wind tunnel were used to specify the concentration values on the inflow boundary. The

model computations made at $s = 60H$ were then compared to the wind tunnel measurements made at the equivalent downwind position.

The conservation of mass equation for tracer gas in the wind tunnel can be written in non-dimensional form as

$$\frac{\partial C}{\partial t} + \frac{\partial \bar{u}C}{\partial s} = \frac{1}{H} \frac{\partial}{\partial s} \left(\lambda_s K_s \frac{\partial C}{\partial z} \right) + \frac{H}{W_d^2} \frac{\partial}{\partial n} \left(\lambda_n K_n \frac{\partial C}{\partial n} \right) + \frac{1}{H} \frac{\partial}{\partial z} \left(\lambda_z K_z \frac{\partial C}{\partial z} \right), \quad (2)$$

where $\bar{u}(s, n, z)$ is the wind speed in the tunnel as determined by the wake theory; s is oriented along the axis of the wake; n is oriented across the wake; z is the vertical axis; C is the concentration; and λ_i is the turbulence length scale in the i -th direction. The eddy diffusion coefficients are assumed to have the form

$$\bar{K}_i = U_\infty \lambda_i K_i. \quad (3)$$

It was assumed that $\bar{v}$ and $\bar{w}$ were zero in the above equation, which should be a good assumption for $s > 30H$.

Equation (2) was solved by the same numerical techniques used in the original ROADWAY model (Eskridge *et al.*, 1979). Equation (2) was approximated

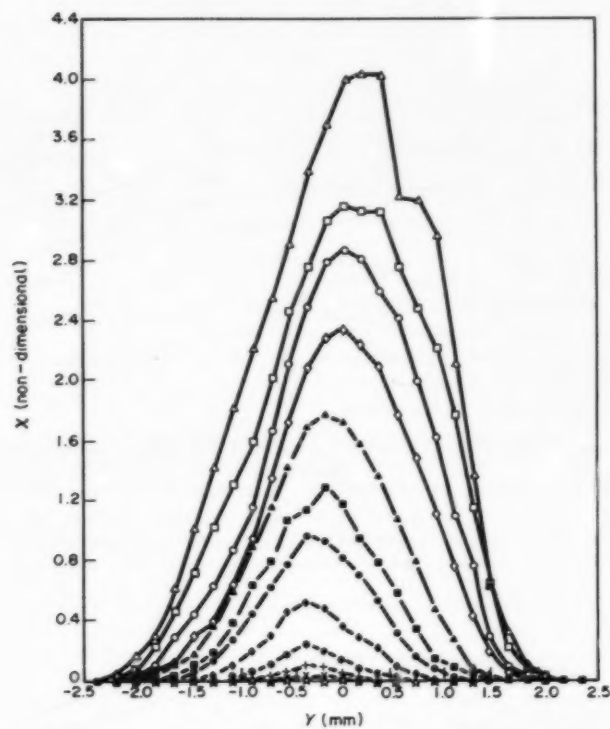


Fig. 3. Lateral profiles of nondimensional concentration at $s = 30H$ measured in $H/4$ increments with $\Delta - H/4$, $\square - H/2$, $\circ - 3H/4$, etc.

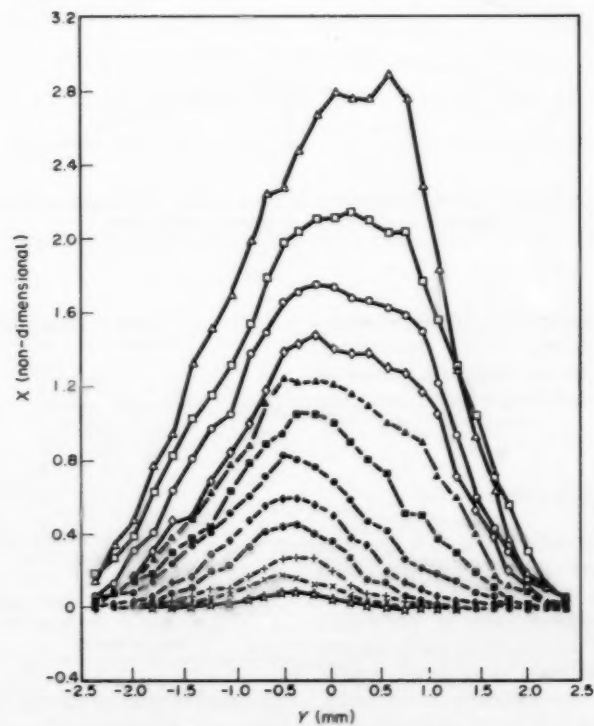


Fig. 4. Same as Fig. 3 except at $60H$.

Table 3. Comparison between model results in original version and current version for 1157 data points using the GM data

	ROADWAY 1979	ROADWAY 1985
Intercept	0.10	0.05
Slope	0.90	1.18
Correlation	0.82	0.87
rms error	0.46	0.49

independent of the GM sulfate experiment data, whereas the 1979 version used the GM data to determine five coefficients needed in the wake theory. These coefficients have now been determined from the wind tunnel data of Eskridge and Thompson (1982). Table 3 shows a limited comparison of the two versions of the model. A more detailed statistical analysis of the ROADWAY model tested against the GM data is given in the companion paper by Rao *et al.* (1986). The old and new model results were comparable, except that the correlation had improved and the slope of the least-squares linear fit had increased in the revised version. The increase in slope is actually an improvement, as the model should over-predict when the wind direction is within ± 30 degrees of the orientation of the road. Under parallel wind directions, wind meander is important in diffusing the vehicle pollutants, and as previously mentioned, ROADWAY does not attempt to parameterize wind direction variation.

The conclusion drawn from Table 3 is that previous modifications to the wake theory and those reported here have improved the ROADWAY model over its initial version.

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APPENDIX

a. The conservation of species equation

The general form of a conservation of species equation in two dimensions is

$$\frac{\partial C}{\partial t} + \nabla \cdot C\mathbf{V} = \nabla \cdot K\nabla C + E + R, \quad (\text{A1})$$

where ∇ is the divergence operator in (x, z) coordinates; E an emission source term; K is the eddy diffusivity tensor; C is the concentration of some chemical species; and R is a chemical production or removal term.

One of the main assumptions made is that a reference atmosphere exists, describable by surface layer similarity theory to which the perturbations due to the vehicles can be added, i.e.

$$K_x = K_x^s(z) + K_x^w(x, z), \quad (\text{A2})$$

$$K_z = K_z^s(z) + K_z^w(x, z),$$

where K_x^s and K_z^s are eddy diffusion coefficients from the similarity and wake theories, respectively. Similarly, the wake velocity deficit is added to the wind field described by similarity theory to yield the total wind field.

Physical reasoning and numerical stability require that $\nabla \cdot \mathbf{V} = 0$, hence the continuity equation is solved to yield w , the vertical velocity, which is not zero along the road due to the presence of the vehicle wakes.

b. The boundary conditions

The problem of imposing boundary conditions is always difficult in atmospheric modeling, especially when the scale of the problem is small. In this model, it is assumed that the concentration gradient at the surface is zero, i.e.

$$\frac{\partial C}{\partial z} = 0, \quad (\text{A3})$$

which implies no losses at the surface. At the side boundaries the following conditions are imposed

$$\text{Outflow: } \frac{\partial C}{\partial x} = 0, \quad (\text{A4})$$

$$\text{Inflow: } C = \text{Background.}$$

At the top boundary it is assumed that the concentration is equal to the background at that height

$$C = \text{Background.} \quad (\text{A5})$$

These boundary conditions [Equations (A4) and (A5)] are not perfect physical constraints as they are imposed primarily for mathematical reasons. It has been found in numerical experiments that the model results were more sensitive to the height of the modeling region than to any boundary condition. Therefore, when the winds are light or parallel to the roadway, the height of the integration region is raised.

c. The grid

The numerical solution of Equation (A1) requires that it be expressed in finite differences on a grid. The numerical scheme of Zalesak (Eskridge *et al.*, 1979) allows variable grid spacing in the horizontal and vertical directions. The grid also varies according to the wind speed and direction and the number of highway lanes.

d. The numerical scheme

Equation (A1) can be written in operator form as

$$\frac{\partial C}{\partial t} + \sum_{n=1}^4 B_n(C) = E + R, \quad (\text{A6})$$

where B_1, B_2, B_3 and B_4 are linear operators and represent the flux and diffusion terms, respectively. Equation (A6) can be approximated by

$$\frac{C_{ik}^{n+1} - C_{ik}^n}{\Delta t} + \sum_{m=1}^4 L_m(C_{ik}) = E_{ik} + R_{ik}, \quad (\text{A7})$$

where $L_m, m = 1, \dots, 4$ are approximations of B_m . Equation (A7) is solved by a fractional step method. The procedure is as follows where we assume $R = 0$:

$$C^1 = C^n + \Delta t L_1(C^n), \quad (\text{A8})$$

$$C^2 = C^1 + \Delta t L_2(C^1), \quad (\text{A9})$$

$$C^3 = C^2 + \Delta t L_3(C^2), \quad (\text{A10})$$

$$C^4 = C^3 + \Delta t L_4(C^3), \quad (\text{A11})$$

$$C^{n+1} = C^4 + \Delta t \cdot E. \quad (\text{A12})$$

The operators L_3 and L_4 are simple, centered in space approximations, while the operators L_1 and L_2 , which solve the advection terms, are based on the flux-corrected algorithm of Zalesak. This algorithm is an upstream scheme which insures nonnegative values for the concentration at every grid point. The algorithm reduces numerical diffusion and is stable for

$$\Delta t \leq 0.5 \Delta x / u_{\max}.$$

e. The basic state atmosphere

The basic state or upwind atmospheric conditions are determined by surface layer similarity theory which requires the specification of the vertical temperature gradient and the wind velocity. From this information, vertical profiles of u , v , K_z , and K_x were generated.

f. Review of the wake theory

The vehicle wake theory was developed by Eskridge and Hunt (1979), and modifications have been made based upon wind tunnel experiments by Eskridge and Thompson (1982) and Eskridge and Rao (1983). All unknown constants in the wake theory are now based upon wind tunnel measurements. A brief description of those studies is given in this section.

The wake velocity deficit of a single vehicle is given by

$$u_D = QA(\bar{\eta})^{-0.75} f(\bar{\eta}/l(s), \bar{z}/l(s)) \quad (\text{A13})$$

where

$$s = s/H, \quad z = z/(\gamma AH), \quad n = n/(\lambda \gamma AW_d),$$

and H is the height of the vehicle; Q is the windspeed relative to the vehicle; A is the strength of the wake determined by the overturning moment acting on the vehicle, given by

$$A^4 = C_d (32\pi e^{1/2} \lambda \gamma^3)^{-1}, \quad (\text{A14})$$

where C_d is the drag coefficient; γ and λ are constants with experimentally determined (wind tunnel) values of 0.095 and 1.14, respectively; s is the coordinate along the centerline of the wake; n is the coordinate in the horizontal plane perpendicular to s ; z is the vertical coordinate (see Fig. A1); $l(s)$ is the vertical scale length of the wake and is given by

$$l(s) = \gamma AH(\bar{s})^{0.25}.$$

The function f in Equation (A13) is the solution to a partial differential equation which does not have a closed form solution. However, the equation is separable and

$$f(\bar{\eta}/l(s), \bar{z}/l(s)) = Y(\bar{\eta}/l(s))T(\bar{z}/l(s)), \quad (\text{A15})$$

where

$$Y(\bar{\eta}/l(s)) = C_1 \text{EXP}[-\bar{\eta}^2/8l^2(s)].$$

$T(\bar{z}/l(s))$ was found by fitting a polynomial to wind tunnel measurements of velocity deficit

$$T(\bar{z}/l(s)) \equiv T(\xi) = \sum_{i=1}^6 b_i \xi^{i-1} + b_0. \quad (\text{A16})$$

The coefficients $b_0, \dots, b_6$ are given in Table A1.

The turbulent kinetic energy terms are given by

$$(\bar{u}^2, \bar{v}^2, \bar{w}^2) = (a_1, a_2, a_3) A^2 Q^2(\bar{s})^{-1.2} F_c(\chi, \omega), \quad (\text{A17})$$

where

$$\chi = n/(W_d s^{0.4}), \quad \omega = z/(H s^{0.4}),$$

and u and v are oriented in the s and n directions, respectively. The constants a_1, a_2 , and a_3 were evaluated from wind tunnel data and were found to be 0.048, 0.040 and 0.030, respectively. The function F_c was determined by a least-squares ortho-

Table A1. Constants for the polynomial fits in Equations (A16) and (A18)

Surface fit		Curve fit	
Ψ_{00}	0.3511237×10^{-1}	b_0	0.0179349
Ψ_{01}	0.1255308×10^2		
Ψ_{02}	-0.4796241×10^2	b_1	2.576580
Ψ_{03}	0.6732523×10^2		
Ψ_{04}	-0.3572466×10^2	b_2	-2.3062584
Ψ_{20}	-0.1890581	b_3	0.8951468
Ψ_{21}	-0.9345507×10^1		
Ψ_{22}	-0.1821427×10^3	b_4	-0.1758604
Ψ_{23}	0.5617911×10^3		
Ψ_{24}	-0.3995373×10^3	b_5	0.0169970
Ψ_{40}	0.2649465		
Ψ_{41}	-0.9434068×10^2	b_6	-0.0006404
Ψ_{42}	0.1034830×10^4		
Ψ_{43}	-0.2348153×10^4		
Ψ_{44}	0.1510437×10^4		

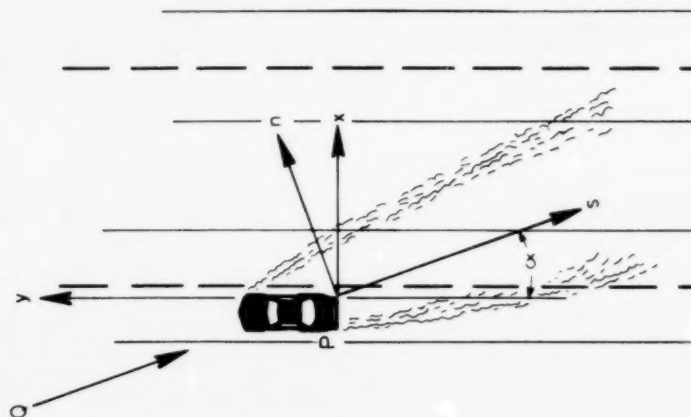


Fig. A1. The (s, n, z) coordinate system oriented along the wake and normal to it, whereas the (x, y) system is fixed in the standard east-west, north-south orientation.

gonal polynomial fit to wind tunnel data and is given by

$$F_c(\chi, \omega) = \sum_{n=0}^4 \sum_{m=0}^2 \psi_{2m,n} \omega^n \chi^{2m}, \quad (\text{A18})$$

subject to the restriction that $F_c > 0.0$. The constants in Equation (A18) are listed in Table A1.

The observed wind velocity fluctuations at some fixed point near a roadway are due to three distinct causes. Clearly, velocity fluctuations are produced by the wake turbulence described by Equation (A17) as well as by the ambient turbulence. Fluctuations will also occur because of the time variation in the wind velocity as a vehicle's wake passes the fixed point. This wake-passing effect is clearly not turbulence, but an artifact of the fact that the data are taken in the Eulerian rather than Lagrangian frame of reference.

Let the superscripts p and w and the subscript ∞ represent the wake-passing effect, the wake turbulence and the ambient turbulence, respectively. The total velocity variance is assumed, as a first approximation, to be determined by adding the components, so that

$$\overline{u'^2} = \overline{u'^2}^p + \overline{u'^2}^w + \overline{u'^2}^\infty, \quad (\text{A19})$$

with similar expressions for $\overline{v'^2}$ and $\overline{w'^2}$. It should be noted that Equation (A19) assumes there are no interactions between the various scales of turbulence. The total velocity variance energy is defined by

$$\sigma^2 = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2,$$

with similar definitions for the ambient, wake, and wake-passing velocity variances. It should be noted that while the wake-passing turbulence can be very large, it is nondiffusive, and one is interested in it only as a feature of the vehicle wake theory and in the analysis of roadway data.

The equations describing multi-vehicle wind velocity, turbulence and wake-passing effect are presented below. The derivations for these equations are given in Eskridge and Rao (1983).

The horizontal wind velocity components are computed by

$$\begin{aligned} \overline{u(x_0, t)} &= \overline{U_\infty(z_0, t)} - \frac{1}{TV_h} \sum_{j=1}^N \int_{-TV_{h/2}}^{TV_{h/2}} u_{Dj}(x_0, y/V_h) \sin \alpha \, dy, \\ \overline{v(x_0, t)} &= \overline{V_\infty(z_0, t)} - \frac{1}{TV_h} \sum_{j=1}^N \int_{-TV_{h/2}}^{TV_{h/2}} u_{Dj}(x_0, y/V_h) \cos \alpha \, dy, \end{aligned} \quad (\text{A20})$$

where V_h is the average vehicle speed; $x_0 = (x_0, y_0, z_0)$; u_{Dj} is given by Equation (A13), N is the number of vehicles passing the point x_0 during time interval $(-T/2, T/2)$; α is the angle between the relative wind Q and the highway; and $U_\infty(z_0, t)$

and $V_\infty(z_0, t)$ are upwind ambient conditions.

The turbulent kinetic energy component along the x -axis is given by

$$\overline{u'^2(x_0, t)} = \frac{1}{TV_h} \sum_{j=1}^N \int_{-TV_{h/2}}^{TV_{h/2}} \overline{u'^2(x_0, y/V_h)} \, dy, \quad (\text{A21})$$

where $\overline{u'^2}$ is given by Equation (A17) and similar expressions are found for $\overline{v'^2}$ and $\overline{w'^2}$.

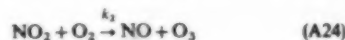
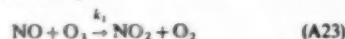
The velocity variance due to wake-passing is given by

$$\begin{aligned} \overline{u'^2(x_0, t)} &= \frac{1}{TV_h} \sum_{j=1}^N \int_{-TV_{h/2}}^{TV_{h/2}} \left[U_j(x_0, y/V_h) \begin{Bmatrix} \sin \alpha \\ \cos \alpha \end{Bmatrix} \right. \\ &\quad \left. - \begin{Bmatrix} u(x_0, t) \\ v(x_0, t) \end{Bmatrix} \right]^2 \, dy, \end{aligned} \quad (\text{A22})$$

where $U_j = |D_\infty, V_\infty| - u_{Dj}$. Equations (A20), (A21) and (A22) are integrated by use of Simpson's method.

g. Chemistry

The roadway model assumes that one is interested in the physical processes which occur within approximately 100 m of the roadway. For this length scale and reasonable cross-wind velocities, the length of time the vehicle emissions are close to the road limits the applicable chemistry. It has been assumed that the following reactions are the only ones of importance near a roadway:



where k_1 and k_2 are chemical reaction rate constants with values of $22.0 \text{ ppm}^{-1} \text{ min}^{-1}$ and $0.46 \text{ ppm}^{-1} \text{ min}^{-1}$, respectively. These reactions lead to the following conservation of species equations:

$$\frac{\partial A}{\partial t} + \nabla \cdot AV = \nabla \cdot K \nabla A + E_A - k_1 DA + k_2 C, \quad (\text{A25})$$

$$\frac{\partial C}{\partial t} + \nabla \cdot CV = \nabla \cdot K \nabla C + E_C + k_1 DA - k_2 C, \quad (\text{A26})$$

$$\frac{\partial D}{\partial t} + \nabla \cdot DV = \nabla \cdot K \nabla D + E_D - k_1 DA + k_2 C, \quad (\text{A27})$$

where A , C and D represent the concentration of NO , NO_2 and O_3 , respectively. The vehicle emissions are in $\text{g} (\text{km veh})^{-1}$.

NOTICE

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